Harmonic Variations in Three-phase Induction Motors Fed by PWM Inverter with Different Stator Coil Pitches

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Abstract:- A sinusoidal pulse-width modulation (SPWM) inverter feeding five different chorded three-phase induction motors were tested for low-order odd harmonic voltage component and efficiency at different loads. Total harmonic distortion (THD) due to 3rd, 5th, 9th, 11th and 13th harmonics were less in a motor with (1-7) 120^o coil pitch. Particular harmonic order for each coil pitch was suppressed and the increasing quantity of efficiency in a motor with (1-6)100^0 coil pitch was increased by 4,92 %. The full pitch motor with (1-10) 180^o coil pitch has more harmonics than other motors.

Keywords :- Coil pitch; Chording; Harmonics; Stator winding

1. Introduction

Due to the increasing requirement of precise control and equipment performance of a modern facility, the appearance of voltage harmonics in the power system has drawn great attention recently. In a power system, induction motors constitute the largest component of the load and are widely used in industrial, commercial and residential applications. Once the power system gets polluted harmonics, the operation characteristics of induction motors will be affected first. Therefore, studying the impacts of induction motors under harmonic voltages has drawn the attention of many researchers. Variable speed drives employing sinusoidal pulse-width modulation (SPWM) inverter fed induction motors are now widespread throughout industry. Unfortunately, losses in an inverter fed machine are always greater than those for the same machine operating on a sinusoidal supply and in some cases this requires derating of the motor [1]. Rotating machines are considered a source of harmonics [2,3] because the windings are embedded in slots which can never be exactly sinusoidally distributed so that the mmf is distorted. Low-order harmonics have a larger impact on the three-phase induction motor than that of high-order harmonics [4]. One method to reduce the low-order harmonics is to adopt chording (fractional pitch) of the stator winding. This paper explains the effect of chording on three-phase squirrel-cage induction motors fed from a three-phase inverter.

2. Chorded (fractional-pitch) windings

A chorded winding is a winding whose coil sides are less than a pole pitch apart, thus saving copper. Pitch factor is the ratio of coil voltages for a fractional-pitch winding to those for a full-pitch one.

$$k_{p1} = \sin\left(\frac{\beta}{2}\right) < 1 \qquad (1)$$

Where β is the coil span in °electrical, $\beta = s\alpha$; s is the coil span in slots. Accounting for harmonics, the pitch factor would be:

$$k_{ph} = \sin\left(\frac{\beta h}{2}\right) \qquad (2)$$

$$\frac{k_{ph}}{k_{p1}} = \frac{\sin(\beta h/2)}{\sin(\beta/2)} \qquad (3)$$

where h is the harmonic order.

3. The winding factor

In the presence of harmonics, the winding factor becomes:

$$k_{wh} = k_{dh} k_{ph} \qquad (4)$$

so that:

$$\frac{k_{wh}}{k_{w1}} = \frac{k_{dh}k_{ph}}{k_{d1}k_{p1}} = \frac{2\sin(\alpha/2)\sin(\pi h/6)\sin(\beta h/2)}{\sin(\alpha h/2)\sin(\beta/2)} \quad (5)$$

where $\beta = s\alpha$.

4. Related definitions and classifications of harmonics

It is well-known that voltage and current harmonics in the power system can come from a number of sources in the network. Theoretically, any nonsinusoidal periodical waveform can be transformed into a different order harmonic waveform through Fourier analysis. Therefore, the nonsinusoidal voltage and current waveform can be expressed as:

$$v(t) = \sqrt{2}\left[V_1 \sin\omega_o t + \sum_{k=2}^{\infty} V_k \sin(k\omega_o t + \phi_k)\right] \quad (6)$$

$$i(t) = \sqrt{2}\left[I_1 \sin\omega_o t + \sum_{k=2}^{\infty} I_k \sin(k\omega_o t + \theta_k)\right] \quad (7)$$

where

V_1, I_1 are the fundamental voltage and current,

V_k, I_k are the kth order harmonic voltage and current,

ϕ_k, θ_k are the phase angles of the kth order harmonic voltage and current, and

ω_0, is the radian frequency of the fundamental wave.

When a nonsinusoidal voltage source is supplied to a three-phase induction motor, the corresponding slip S_k to the various harmonics can be expressed as:

$$S_k = \frac{kN_s + (1-s)N_s}{kN_s} = \frac{k + (1-s)}{k} \quad (8)$$

According to the rotational direction of magnetomotive force (MMF), the $(3n + 1)^{th}$ order harmonics (positive sequence harmonics) contribute MMF and torque in the positive (forward) direction; the $(3n+2)^{th}$ order harmonics (negative sequence harmonics) provide counter MMF and torque; and the $(3n)^{th}$ order harmonics (zero sequence harmonics) do not contribute any rotating MMF or torque. Although the positive sequence harmonics would add a boost to the positive sequence (forward) torque and thus be beneficial, the heating effects of the harmonics offset the benefit of the positive sequence torque.

According to the definition of IEEE-519 [2], the total voltage harmonics distortion factor (THDv) is defined as:

$$THD_v(\%) = \sqrt{\frac{\sum_{k=2}^{\infty} V_k^2}{V_1^2}} \times 100\% \quad (9)$$

and the amount of voltage distortion due to the kth order harmonic is measured by the voltage distortion
factor (VDF) as:

$$VDF(\%) = \frac{V_k}{V_1} \times 100\% \quad (10)$$

5. Configuration of the experimental system

The configuration of the experimental system is shown in Fig. 1. It consists of a three-phase PWM inverter which gives output by comparing the modulating signal with carrier signal technique at 6kHz switching frequency and supplies 50Hz, 380V (rms) voltage to a three-phase squirrel cage induction motor under test. A digital power analyzer with 3,2 kHz sampling frequency is used to measure the stator voltage harmonics, stator voltage, stator current and input power to the motor. The operating data of the induction motor are transmitted to the PC through RS-485 for later analysis. Each motor was mounted in turn on a drive bed and loaded by an electromagnetic brake which is controlled by the dc voltage applied to the brake provided with two arms, one of which with balance weight for measuring the out put torque of the motor. The brake includes a cooling fan that is supplied by the main voltage. Force applied to the induciton motor is measured with a dynamometer which is mounted on the electromagnetic brake’ s one arm to obtain the applied torque. The stator winding of five commercial, 1100W, 36-slot, three-phase, four-pole squirrel cage induction motors were re-wounded with different coil pitches. The coil pitch for each motor was re-wound to pitch 180^0 (Full pitch, 1-10 slots pitch), 160^0 (1-9), 140^0 (1-8) , 120^0 (1-7) and 100^0 (1-6)

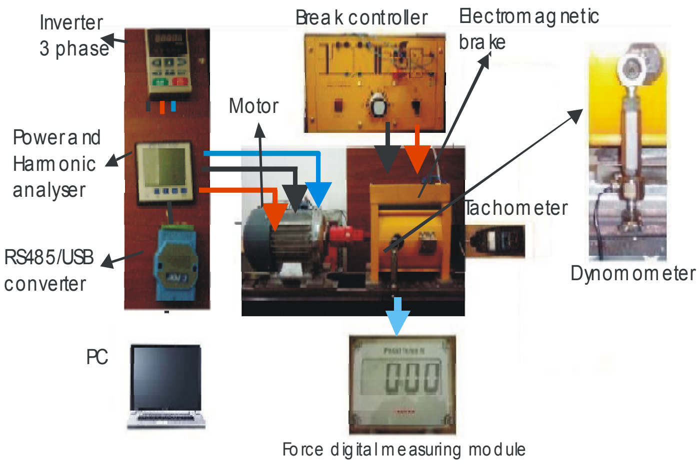

Fig. 1. Experimental setup

for M1, M2, M3, M4 and M5 motors, respectively.All the windings were a simple lap configuration. Fig. 2 shows the three-phase double layer windings embedded in slots.

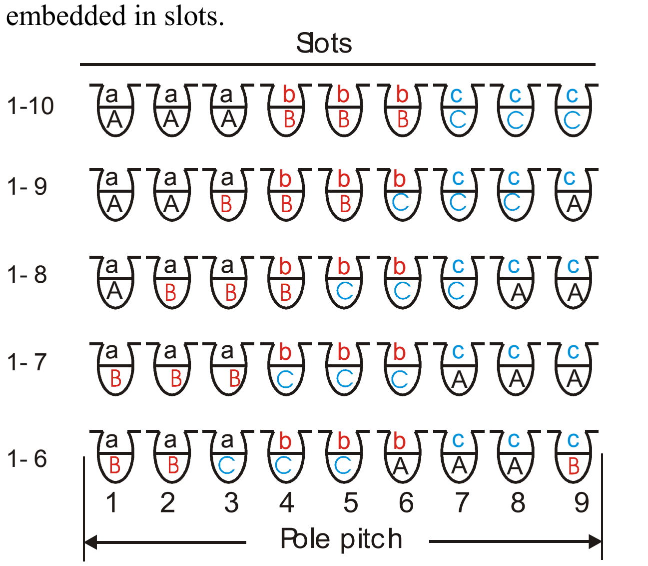

Fig. 2 . Three – Phase winding with two layer configuration in the stator slots

The letters (a,b, and c) indicate the conductors corresponding with phases L_1, L_2, L_3 and their vertical position designate conductors in the same slot. The direction of current is indicated by a, A etc. The pole pitch is 9 slots with 3 conductor slots per pole per phase. The slot pitch is 20^0 so for full pitch winding the coil pitch is 180^0 and the coil pitch is reduced by 20^0 each time for other motors resulting in coil pitch of 160^0, 140^0, 120^0 and 100^0 respectively. To measure the winding temperature, K-type thermocouples were attached to the stator winding of all five motors. Motors were loaded with applied torque of from 1 to 9,74 Nm (full load was 8,18 Nm). The power and harmonic analyser employs the fast Fourier transformation to obtain the harmonic voltage components with PWM supply was used.

6. Results

Figs. 3–5 are the stator low-order voltage harmonics for the different motors with (1-10), (1-9), (1-8), (1-7) and (1-6) coil pitch at half load, full load and overload, respectively. If the coil pitch is shortened by 1/n of the pole pitch then the nth harmonic will be suppressed or the harmonics near to n will be with low voltage, because of the harmonic cancellation at that coil pitch[3].

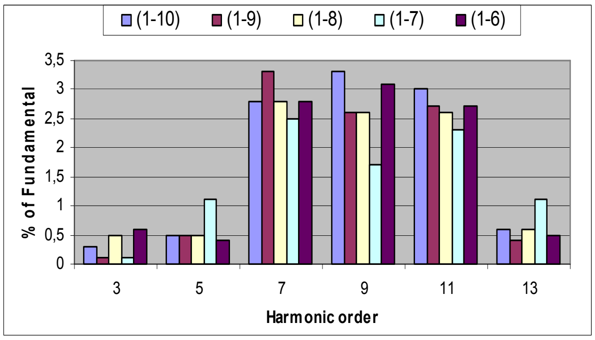

Fig.3. Low – order voltage harmonics at half load.

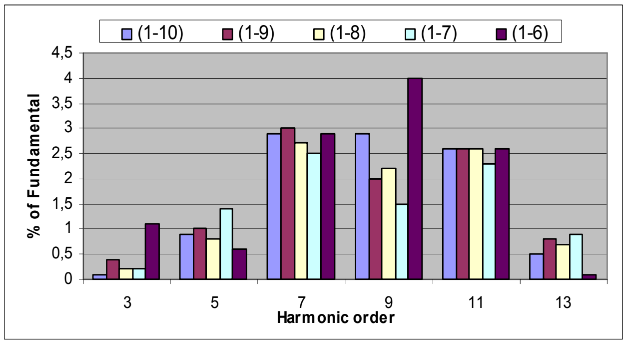

Fig. 4. Low – order voltage harmonics at full load.

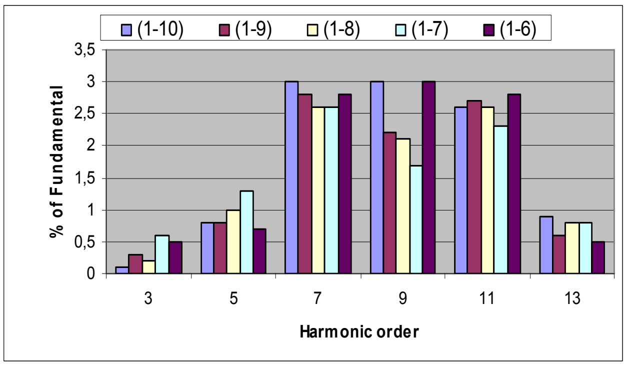

Fig. 5. Low – order voltage harmonics at over load.

As the motor full pole pitch is (1-10) and for M5 (1-6) motor the coil pitch is reduced by 44,44 % of the full pole pitch, the 5th harmonics voltage is reduced dramatically compared to other motor with a different coil pitch. The same effect occurs at all loads as seen from Figs. 3–5. If we consider motor M4 (1-7), the coil pitch is reduced by 33.33% of pole pitch, so the 3th, harmonics voltage is reduced at half load and at full load. Also the 7th, 9th and 11th order harmonics voltages are reduced as seen in Figs. 3–5.

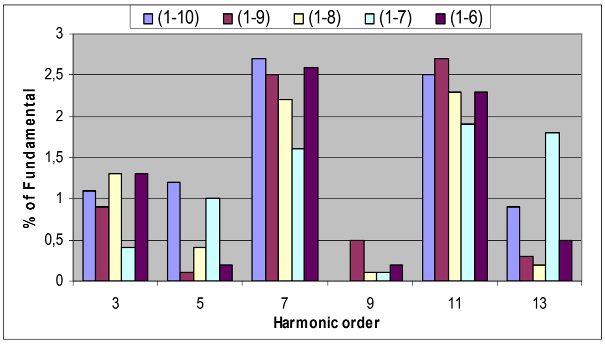

Fig. 6. Low – order current harmonics at half load

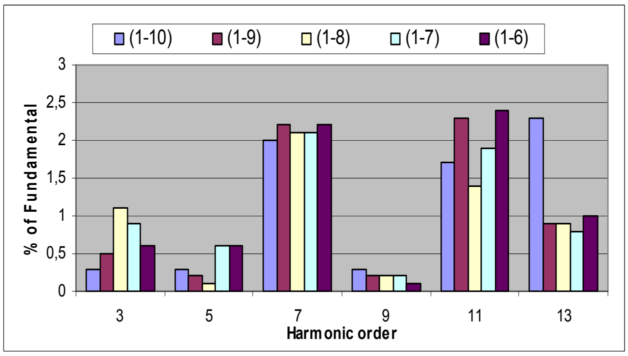

Fig. 7. Low – order current harmonics at full load

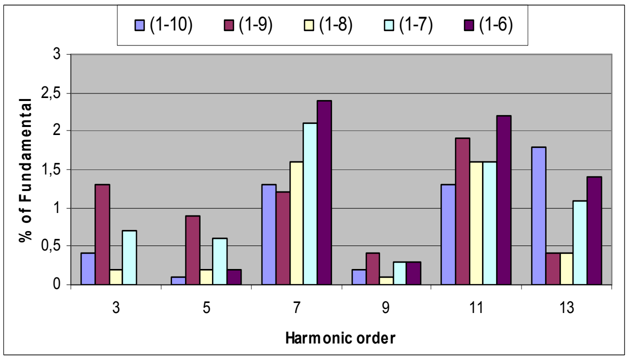

Fig. 8. Low – order current harmonics at over load

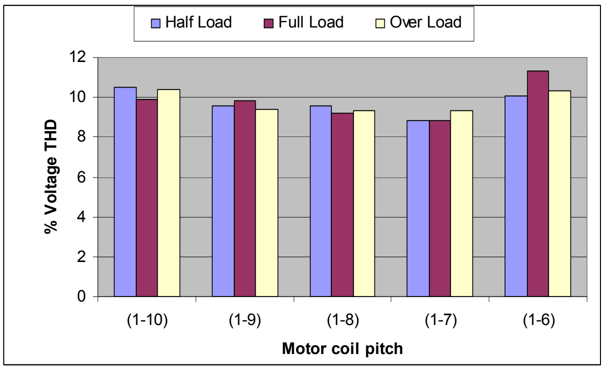

Fig. 9. Total harmonic distortion at different loads.

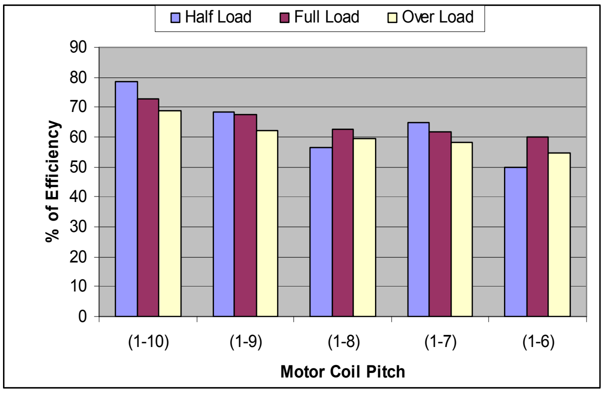

Fig. 10. Efficiency at different motors

In motor M3 (1-8) the coil pitch is reduced by 22.22%, the 5th harmonics is suppressed at all load in fig. 6-8. The 7th harmonics is less than in the (1-9) and (1-10) motors (Fig. 6). If we consider motor M2 (1-9) the coil pitch is reduced by 11,11%, the 13th harmonics voltage and current are reduced compared almost all motors with different coil pitch. If we consider M1 with coil pitch (1-10), upper and lower slots have the same phase and direction of currents in each slot. But for motor M2 (1-9) the slot numbers 3, 6 and 9 have two different phase conductors with different current directions, thus overlapping between adjacent phase-bands benefits on their air gap flux pattern [6]. This overlapping is bigger in motor M3 and even higher in motor M4 and also higher in motor M5. So there are more possibilities of harmonics cancellation in motor M5. But if we see the THD due to 3rd, 5th, 9th, 11th and 13th for five motors at three different loads, motor M2 with (1-9) coil pitch and M3 with (1-8) coil pitch have less harmonics compared with the other motors both for current and voltage in fig. 9-10. has lowest harmonics and other motors have more. This is due to the aiding of a low-order odd harmonics (3rd, 5th and 9th) due to overlapping of MMF waveform caused by chording of coil. This aiding of harmonics is less in motor M2 than in other motors. The effect of chording can also be seen in THD in current due to 3rd, 5th, 9th, 11th and 13th harmonics (Fig. 9). Fig. 10 shows that the efficiency of motor M5 (1-6) at all load is less than the others. This is due to the increase in flux caused by the decrease of pitch factor. This increase in flux causes more core losses. However the increasing quantity of efficiency was increased 4,92 % so there is a significant effect of the winding design at over load.

7. Conclusions

Low-order harmonics in stator voltage of three phase induction motor fed by PWM voltage could be reduced by chording the stator winding. This suppresses particular harmonic components with different type of coil pitch but also aids the other low order harmonics. Motor M1 is considered efficient however increasing quantity of efficiency decreased. The increasing quantity of efficiency was increased when the low order harmonics up to 13th were dealt with and motor M5 efficiency was increased 4,92 % so there is a significant effect of the winding design at over load. The full pitch motor has more harmonics than other motors.

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